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Forecasting water budget deficits and groundwater depletion in the main fossil aquifer systems in North Africa and the Arabian Peninsula

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A R T I C L E I N F O

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A B S T R A C T

We develop a water budget model that quantifies and forecasts water deficits and groundwater depletion of the main exploitable fresh fossil aquifer systems in North Africa and the Arabian Peninsula under different climatic and socio-economic scenarios from 2016 until 2050. Our results suggest that in the upcoming few decades, under the most plausible climatic and socio-economic scenario (SSP2-AVG), within North Africa, only Egypt and Libya will experience severe water deficits with respectively ~45% and ~90% of their current water budget in 2050. For the Arabian Peninsula, all countries will undergo water deficits, ranging from ~20% for Saudi Arabia to almost double the supply for Yemen (~190%). Under these alarming deficits, resulting from severe anthropogenic discharges, the majority of the small to mid-size exploitable fossil aquifer systems in the Arabian Peninsula could reach full depletion by 2050 and the total depletion of groundwater resources in all aquifer systems could be reached in ~60–90 years. Over the same time span, North African fossil aquifers will lose 1–15% of their exploitable fresh water volume and may reach total depletion in ~200–350 years with the projected increased extraction rates. We find that the major cause of the water budget deficit and groundwater depletion in the MENA area are anthropogenic drivers rather than climatic ones. Finally, we conclude that if current hydrologic, climatic and socio-economic trends continue, the nations with the lowest gross domestic product per capita, like Egypt, Yemen and Libya, will undergo the highest water deficit per capita, leading to a significant rise in food prices, potentially resulting in more socio-economic instabilities over the next three decades.

1. Introduction

Most areas of North Africa and the Arabian Peninsula are classified as hyper-arid environments, with an aridity index (i.e. the ratio between the mean annual precipitation and mean annual potential evapotranspiration) below 0.03 (Penman, 1948; UNESCO, 1979). The average water availability per capita in the countries located in these areas is ~1100 m^3 per year (World Bank, 2007), which is below the water security threshold of 1700 m^3 per year proposed by Falkenmark et al. (1989), defined as the measure of annual water availability per capita within the country or region. Luo et al. (2015), suggest that in 2040, 14 of the 33 most water-stressed countries will belong to this area, including nine having a score of 5.0 out of 5.0 on the water stress index (defined as the ratio of water withdrawal to water availability).

North Africa and the Arabian Peninsula comprise several countries with a substantial diversity in natural resources availability and wealth, economic and governmental structures, and population growth rates. Despite these differences, they strongly depend on groundwater resources for their development. Some of the world largest fossil aquifer systems extend throughout this geographic area, serving as the only natural strategic freshwater reserve for the region. Within North Africa, the Nubian Sandstone Aquifer System (NSAS), the Murzuq Aquifer and the North Western Sahara Aquifer System (NWSAS) serve as the major groundwater supplies for Algeria, Tunisia, Libya, Egypt, Chad and Sudan; while for the Arabian Peninsula, numerous aquifers contribute to the water needs of the Gulf Cooperation Council (GCC) countries and Yemen (Fig. 1).

The challenges in the current water scarcity scenarios are accentuated by the forecasted increase in temperature and reduced precipitations, which will lower the volume of water recharge for

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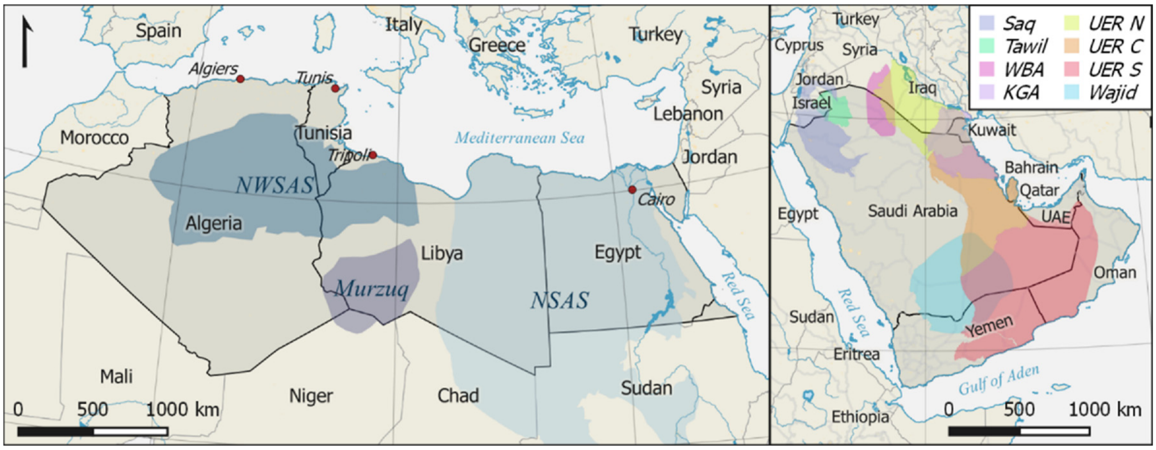

Fig. 1. Map of the areas under study showing national boundaries and the extent of the regional fossil aquifer resources.
Figure based on the 2015 IGRAC World Map of Transboundary Aquifers (IGRAC, 2015).

renewable water resources (Sowers et al., 2011; Barros et al., 2014; Wodon et al., 2014). Population growth projections, combined with urbanization and economic development, will also increase the water demand, resulting in serious hazards for food security and poverty reduction. Moreover, it is difficult to assess the aquifers' water budget, due to the large uncertainties in total groundwater storage (Richey et al., 2015).

Considering all of the above a thorough understanding of the dynamics of aquifer systems under climatic and socio-economic uncertainties is crucial to forecast water budgets, deficits and water demands. Early developments in water budget modeling by Korzoun et al., 1978; Gleick, 1989; Falkenmark et al., 1989, provide a first-order assessment of the evolution of the global water balance. These global water studies are further developed by integrating the potential impacts of climatic and socio-economic changes (e.g. Arnell et al., 1996; Shiklomanov, 1997; Alcamo et al., 1997; Vörösmarty et al., 1998; Arnell, 1999). Recent water budget models account for the variability of groundwater resources (e.g. Gleeson et al., 2012; Gleeson and Wada, 2013; Taylor et al., 2013; Döll et al., 2014; Wada et al., 2014) and consider time-variable increases in water demand (e.g. Rosegrant et al., 2002; Ercin and Hoekstra, 2014). Due to their global approach, many of the above-mentioned models successfully characterize the current hydrological conditions of global aquifer systems, but cannot be applied to determining water deficits at country-level for our study area, as they do not incorporate the local hydrological and climatic forecast complexities. In contrast, the existing regional water budget models are mainly focused on localized basins, catchments or groundwater systems, which do not account for the local water imbalances (e.g. Alsharhan et al., 2001; Voss et al., 2013; Ahmed et al., 2011, 2014) and their socio-economic impacts. The frequent instabilities in the Middle East and North Africa (MENA) area have caused an emerging interest in regional water budget models to integrate macroeconomic aggregate variables and thereby constrain the ambiguities of current water supply and demand projections (e.g. Immerzeel et al., 2011; Droogers et al., 2012). A coherent assessment of the intrinsic relationship between hydrologic and socio-economic factors, as well as their time scales and future projections, remains critical for these highly water-stressed countries. To address this uncertainty, we establish a water budget model that combines country-level demographic, macroeconomic, water supply and demand data in order to quantify the water deficit volumes per country and the groundwater depletions rates, from 2016 to 2050, for the main aquifer systems in North Africa and the Arabian Peninsula. Finally, we discuss the implications of the projected deficits and their role in the socio-economic stability of these countries for the upcoming decades.

2. Methodology

We develop a water budget model that allows us to quantify the total simultaneous deficits and groundwater depletions, while accounting for climatic and macroeconomic drivers affecting the national and transboundary water resources in North Africa and the Arabian Peninsula. In particular, we calculate the time scale and volume depletion for each major exploitable fresh aquifer in this region under three climatic and five macroeconomic scenarios. The timespan of the simulation is set from 2016 to 2050 with a yearly time step. The year 2016 is considered the base year; for the period 2017–2050 we calculate the forecast related to water supply and demand. We select this mid-range time frame for two main reasons: (1) to avoid large errors and uncertainties arising from long-term projections of input variables; and (2) to emphasize the critical changes in the water budget that will occur in the short- and mid-term.

Fig. 2 shows the flow diagram of our water budget model. The model is organized in two main parts: water demand (in red) and water supply (in blue). The demand side includes all water requirements for each economic sector, i.e. agricultural, industrial and municipal requirements for each country. These, in turn, depend on macroeconomic factors such as population, gross domestic product (GDP), cropland cover and electricity production projections, which are based on different Shared Socio-economic Pathways (SSPs) scenarios described in detail in Section 3.1. For the supply side, we classify the water resources into two major groups: conventional sources, comprising renewable (surface and renewable groundwater) and non-renewable water resources, and non-conventional supplies, including desalination and wastewater reuse. In each simulation cycle, the water budget model calculates how much water a given country will need to meet its annual consumption, i.e. the sum of its annual water demands per sector.

The climatic projections for the MENA area suggest with high confidence that average annual temperatures will continue to increase throughout the 21st century (Lelieveld et al., 2016), while the projections showing a reduction in precipitation exhibit higher local variability (Lionello and Giorgi, 2007; Kitoh et al., 2008; Evans, 2009; Christensen et al., 2013).

Hence, evaluating the impacts of such climatic variability on renewable and non-renewable groundwater resources generates additional challenges, due to the complexity of the hydrologic systems and the fact that measurable changes in aquifer storage are often visible only in the long term. In addition, forecasting groundwater recharge, which represents a key parameter for the aquifers' budget, often entails large uncertainties. Results from global hydrological models show that in the southern rim of the Mediterranean Sea there will be a decrease in recharge of more than 70% (Döll and Flörke, 2005). Several other

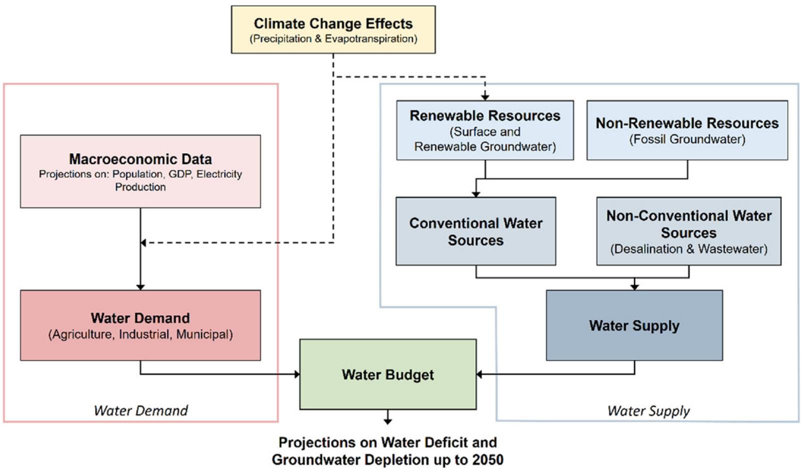

Fig. 2. Flow diagram of the water balance model developed in this study. On the left side is the water demand per economic sector, while on the right side, the water supply combining conventional and non-conventional water resources. Results are presented as projections of water deficit and groundwater depletion volume (2016–2050).

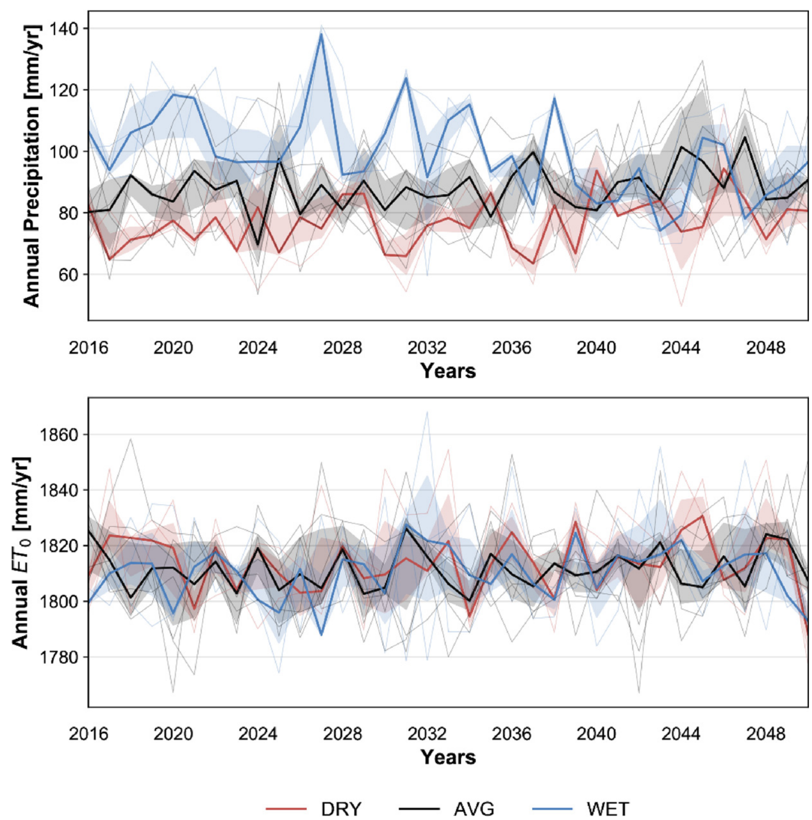

Fig. 3. Total annual precipitation (upper plot) and total annual reference evapotranspiration ET_0 (lower plot) trends from 2016 to 2050 for the twelve climatic projections for Algeria. Highlighted in red, black and blue bold lines are the median values for each of the three resulting marker scenarios, together with their respective first and third quartile represented as shaded areas.

studies, performed at catchment levels, highlight a similar negative trend (e.g. Kunstmann et al., 2007; Ludwig et al., 2012). However, in the MENA region's hyper-arid environments, groundwater recharge is mostly concentrated in periods of flash heavy rains and associated floods (Vogel and Van Urk, 1975; Al-Sefry et al., 2004). Moreover, recent studies have observed a potential increase in the focused recharge of some aquifer systems in the area during rare intensive rainfall events (Taylor et al., 2013; Hartmann et al., 2017). While there are several uncertainties in the groundwater recharge projections for arid environments, anthropogenic overexploitation is the most predominant factor impacting aquifer depletion rates (Wada, 2016; Rodell et al., 2018). The intensification of drought phenomena, coupled with population increase, urbanization and rapid economic development will further aggravate the present conditions.

Given the complexity of the above described phenomena, climate change impacts are reflected in our model as an alteration of both monthly temperatures and precipitation amounts. The temperature increase translates in higher evapotranspiration, which combined with rainfall variability directly affect our estimation of the agriculture water demand and the recharge of renewable water resources. A more detailed explanation on the impacts of climate change on water demand is outlined in Section 3, while Section 4 analyses the effects on the renewable water supply.

As a first step in building our climatic projections, we retrieve the dataset of monthly average temperatures (accounting for daily mean, minimum and maximum temperature) and monthly average

precipitations (in volume and in number of rainy days) from the historical Climatic Research Unit (CRU) (Harris et al., 2014); this data spans from 1901 to 2015 and is downscaled to the country-level. To forecast the future trends of temperature and precipitation variations from 2016 to 2050 we use the CRU data combined with the temperature and precipitation variations from Ruosteenoja et al. (2003) for the Sahara (SAH) region using the CSIRO, ECHAM4 and HADCM3 global circulation models and the A2, B2, A1FI, and B1 IPCC-AR4 emissions scenarios, combining them in a total of twelve monthly climatic projections. We only consider the CSIRO, ECHAM4 and HADCM3 circulation models as they provide the most consistent precipitation forecasts for the MENA area. First, we calculate the overall country-based total annual reference evapotranspiration and precipitation for each year from 2016 to 2050. Then, we use the difference between these two variables to classify each of the twelve climatic projections in three marker scenarios: DRY, average (AVG) and WET. We consider as DRY the three climatic projections with the highest difference in precipitation and reference evapotranspiration, while the three with the lowest difference are assigned to the WET group. The remaining climatic projections are considered in the AVG group. In general, we observe that the twelve climatic projections produce highly heterogeneous forecasts for precipitation, while they concur on the steady increase of future mean temperatures, translating in a comparable slowly increasing trend of the reference evapotranspiration forecasts. Fig. 3 provides an example of this classification for the case of Algeria, for which we highlighted the median values and the first and third quartiles for each of the three resulting marker scenarios.

In order to estimate the water deficit, we simulate the projected water gap for all the considered countries assuming that each nation does not increase its fossil groundwater extraction more than its present levels, which we define as "Business as Usual" (BAU). In order to estimate groundwater depletion, we perform the same simulation, but allowing countries to increase their groundwater withdrawals to compensate for the rising country water deficit, which we define as "Increased Groundwater Withdrawal" (IGW). With the simulation of this second case study we are able to calculate the water stress on each groundwater system expressed in terms of aquifer volume depletion. After controlling for IGW, if a country does not have any further available resource to compensate its annual water demand, it will generate a water deficit for the selected year. As most of these aquifers are transboundary, the effects of an increase in groundwater withdrawal can potentially affect the neighboring nations not only by lowering the total amount of available shared water, but also by modifying the groundwater flow patterns and piezometric heads, or by deteriorating the overall water quality of the aquifer. The objective of our model is limited to the estimate of the overall magnitude of the groundwater volume depletion and its timescale for each major transboundary aquifer as consequence of the simultaneous aggregate withdrawal of one or more riparian countries on a regional scale.

2.1. Model error analysis

Water balance modelling is constrained by the uncertainties in the number of variables involved in the calculation and by the time-frame of the simulations. In this section, we address the potential limitations of our model and describe the error analysis that we have performed.

As outlined in the previous section, constraining the uncertainties on the projection of climatic variables is a key parameter for accurate water budget modeling. Unfortunately, these parameters present different ranges of confidence regarding their magnitude and temporal distribution. In particular, an important aspect is the prediction of future interannual variability in precipitation. Several studies have analyzed the region's historical precipitation trends suggesting that while the Arabian Peninsula shows a strong interannual precipitation variability without any specific temporal pattern, in North Africa, changes in rainfall from one year to the other are much smaller (Zhang et al., 2005; Zittis, 2017). If future climatic changes will cause longer periods of drought, this will mostly affect countries such as Algeria and Tunisia that strongly depend on precipitation produced within their territories more than other countries in the MENA region. In order to lower the overall ambiguities in the climatic projections, we combine the products of several GCMs and emission scenarios considered at a monthly-scale and then aggregated on an annual-scale. Further, the forecasts of the anthropogenic drivers used in our model contain estimation errors, especially in the long run. We therefore account for all the five available SSPs in our simulations, in order to capture a wider spectrum of variability.

The scarce availability of published data regarding the water resources of the area under study and their poor consistency across different sources can lead to large uncertainties in the development of a precise country water budget (UN-ESCWA and BGR, 2013). To constrain the ambiguities concerning this aspect, we establish a consistent dataset on the major characteristics of the considered aquifer systems as described in section 4.1.2 (see Table 2) with the most updated and reliable information publicly available. This, however, requires us to perform our simulations at the country level and on an annual-scale to maintain consistency between our entry data. Since this approximation can potentially lead to further inaccuracies in the estimation of variables that are function of climatic parameters, we perform a comprehensive error analysis to assess the resulting uncertainty in model reliability. In particular, for each of the considered variables we calculate the average standard deviation error introduced by the spatial approximation to a single country-level average data. We then derive the resulting propagation error effect throughout the entire simulation by evaluating in every step the induced error for each dependent variable used in the model. Finally, we report the error range for all the parameters presented in our results.

3. Modeling water demand

Water demand is defined as the quantity of water required by a country to meet its agricultural, industrial and municipal needs, and can be further categorized into water use and water consumption. Water use includes the amount of water withdrawn from different sources to fulfill the demand, while water consumption is the portion of water use that is not returned in the water cycle and no longer available for reuse. In our model, we employ the water use approach to quantify the water demand as an input for our water budget calculation. This method allows us to directly link the dependency of demand to the water supply for each country.

Estimates of water demand per country and per sector are based on demographic and economic trends, described by population and GDP growth (Water, U.N., 2009). In the following subsections, we briefly describe each of the components that constitute the structure of our modeled water demand. First, we present the Shared Socio-economic Pathways (SSP) scenarios used in our projections analysis, and afterwards, we describe the method used to forecast water demand for each economic sector.

3.1. Shared socio-economic pathways scenarios

The first step in modeling water demand is the quantification of population and GDP trends, as well as the projection of land use (also referred to as cropland) and future electricity production over the selected time-horizon for the considered countries. In this study, we extrapolate data entries from the 2012–2016 SSPs database, which is an updated version of the Special Report on Emission Scenarios (SRES) by Nakicenovic and Swart (2000). The SSPs represent a new set of classification scenarios produced by the climate change research community to be used for current and future studies on climatic impacts and the consequent evaluation of adaptation-mitigation policies (Riahi et al., 2016). The SSPs are based upon five storylines that are modified

according to the required challenges for the adaptation and mitigation options; similarly to the previous SRES families, they describe alternative socio-economic developments that range from a sustainable path to a fossil-fueled development economy. In particular, SSP1 describes a global shift towards a more sustainable path, with low challenges to mitigation and adaptation; SSP2 is the middle-of-the-road scenario, with medium challenges for both strategies; and SSP3 is outlined as the scenario with higher challenges towards mitigation and adaptation, with strong regional rivalry. In contrast, SSP4 and SSP5 present a world with asymmetric challenges for mitigation and adaptation policies: low challenges for mitigation and high for adaptation in the case of SSP4, and the opposite for scenario SSP5 (Riahi et al., 2016). The International Institute for Applied Systems Analysis (IIASA) has estimated population projections (Samir and Lutz, 2014), while the Organization for Economic Co-operation and Development (OECD) has produced long-term GDP and per capita income projections for each of the five SSP scenarios (Dellink et al., 2015). These data are used as input in our water demand model to calculate projections for population growth and GDP, for which we use World Bank statistics of 2016, hereafter referred to as base year, as initial conditions (World Bank, 2016a, b). In addition, we use the Integrated Assessment Model (IAM) data, centered on the baseline SSP scenarios, to project each country's electricity production and cropland expansion for the MENA region (Riahi et al., 2016; Bauer et al., 2016). The base year values for electricity and cropland areas have been extrapolated from the OECD/IEA, 2015 World Energy Outlook and the FAO AQUASTAT databases, respectively (OECD/IEA, 2015; FAO, 2016a). The resulting projections for aggregate population, aggregate GDP and aggregate electricity production under the five SSP scenarios are shown in Fig. 4 for the two macro regions of North Africa and the Arabian Peninsula.

In North Africa, we observe that population projections for 2050 under the scenarios SSP1, SSP4 and SSP5 show the same trend, with an approximate total number of inhabitants that grows from 151 to 187 million. SSP2, in contrast, represents the intermediate path for population growth, while the highest aggregate population projection is given by the SSP3. SSP2 reaches 204 million in 2050, while SSP3 grows up to 228 million.

The Arabian Peninsula exhibits a different trend for each of the above mentioned SSP storylines. Its population starts at 81 million, and by 2050 it reaches a final aggregate value ranging between 131 and 161 million for SSP1 and SSP4, respectively. Although the North African countries have a higher number of inhabitants in absolute value, the population growth rate for the Arabian Peninsula almost doubles that of North Africa. Population projections from IIASA show that for all of the countries selected in this model, the maximum peak of population increase lies between the years 2050 and 2070, assuming a potential decline afterward. The GDP projections in our model show a rapid increase for both sub-regions, ranging between 1770 and 3250 billion USD from an initial value of ~600 billion USD for North Africa and between 3630 and 5800 billion USD, starting at 1400 billion USD for the Arabian Peninsula. The lower bound is produced by the SSP3 and the upper bound by the SSP5. Within these limits, the storylines are arranged in ascending order as SSP4, SSP2 and SSP1 for North Africa, while this trend is reversed in the case of the Arabian Peninsula. Electricity production is projected to grow extensively, and especially for the SSP5, in which production is projected to increase up to five times the 2016 starting values after 2030. For the other SSP scenarios, electricity production is expected to increase by two to three times in both regions.

3.2. Agricultural, industrial and municipal water demand

The total annual water demand per country, as calculated in our model, is given by the sum of three major components: the agricultural, industrial and municipal water demand, as detailed below. We calculate the water demand per economic sector using data from the FAO AQUASTAT dataset in addition to other independent socio-demographic inputs to derive the model parameters of our water demand regression functions. The use of the FAO AQUASTAT entries for our water demand regression is justified by the need to maintain consistency in the comparison across the countries in our analysis. Different data sources use dissimilar methodologies or classifications methods for calculating and aggregating the final demand values, thus preventing us from reliably combine them together. Since the use of the FAO AQUASTAT data can lead to under- or over-estimate the actual real values, we compare the resulting water demand estimates produced by our model with real data derived from governmental published reports. We obtain an average estimation error < 5% for 2016, accounted singularly for each country. Therefore, for the purpose of this study, we consider the FAO AQUASTAT data as a reliable data-source, as also suggested by numerous authors, e.g. Alcamo et al. (2003); Immerzeel et al. (2011), Droogers et al. (2012).

Water utilization for agriculture accounts for different purposes: irrigation for crops production, livestock and aquaculture. Within these, irrigation requires the biggest share of the water supply, while livestock accounts only for the 0.54% in North Africa and the 0.3% in the Arabian Peninsula (calculated using livestock records from the FAO, 2016b; and the drinking water requirements for livestock from Steinfeld et al., 2006) and negligible requirements for aquaculture, as it is still currently underdeveloped in most of the MENA countries. The annual irrigation water demand for each country is calculated as the product between the country's estimated annual net irrigation water requirements (IWR_y) and the country-specific irrigation efficiency (IE_y) for the considered year y. This efficiency is defined as the ratio between the calculated IWR_y and the actual total agricultural water withdrawal obtained from the AQUASTAT database for each country at the specific year of the FAO survey (FAO, 2016a). To derive the annual net irrigation water requirements, we first retrieve the current crop-type production, crop calendar and cultivated area for each country from Frenken and Gillet (2012). We then calculate the monthly potential evapotranspiration (ET_c) of each specific crop that is equal to the reference evapotranspiration (ET_0) of the considered area multiplied by a

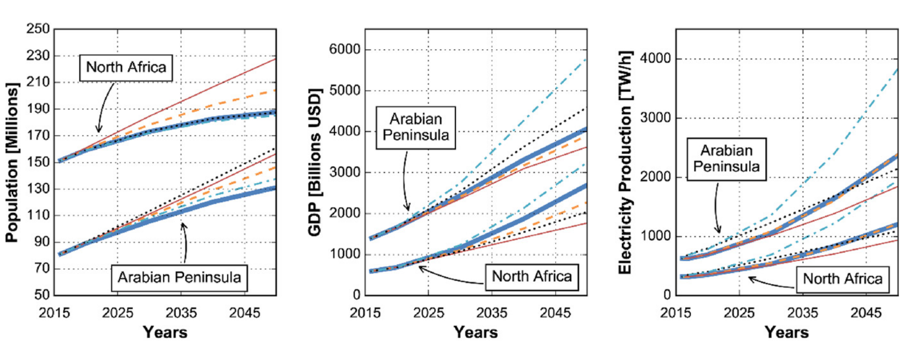

Fig. 4. Trends of aggregate population, GDP and electricity production projections under the five SSP scenarios for North Africa and the Arabian Peninsula (2016–2050). Annual grow rates for population (Samir and Lutz, 2014), GDP (Dellink et al., 2015) and electricity production (Bauer et al., 2016) from the 2012–2016 SSP Database assuming base year data from the World Bank and OECD/IEA databases (World Bank, 2016a, b; OECD/IEA, 2015).

crop-specific coefficient (K_c), which in turn depends on the plant-type and its growing stage as retrieved from Frenken and Gillet (2012). We estimated the monthly average reference evapotranspiration for each country using Hargreaves and Samani's equation (1985) multiplied by the conversion factor 0.408 to obtain the equivalent evaporation in mm/day and by the number of days (N_d) of each specific month:

$$ET_0 = 0.0023\ R_a\ \sqrt{\Delta T}\ (T + 17.8)\ 0.408\ N_d \tag{1}$$

Using the CRU dataset by Harris et al. (2014), we retrieve T, the monthly average mean temperature [C°], and ΔT, defined as difference between the monthly average maximum and minimum temperatures [C°]. The extraterrestrial solar radiation R_a [MJm^{-2}day^{-1}] was instead calculated for each month of the year (we select the middle day of each month) using the equation from Allen et al. (1998). A portion of this water requirement is fulfilled by the plant-available precipitation, which was derived using the historical monthly average precipitation and the number of wet days from the CRU dataset (Harris et al., 2014). The overall monthly difference of these two quantities is then combined with the crop calendar, the monthly cultivated land area and the crop intensity for each specific country, in order to derive the resulting annual net irrigation water requirement. Projecting the evolution of the IWR_y from 2016 to 2050 requires the forecast of the future temperature and precipitation variations in the region during this period. Future monthly mean, maximum and minimum temperatures have been estimated for each country combining historical data randomly selected between the values of the CRU dataset from 1961 to 1990 (Harris et al., 2014) and the projected variations of the specific months resulting from Ruosteenoja et al. (2003) for the Sahara (SAH) region. The interval 1961–1990 is selected in accordance to the climatological baseline period used by Ruosteenoja et al. (2003) in their study. Similarly, we use an analogous approach to estimate the countries' future monthly average precipitations combining historical data and future projections from the same sources described herein. As outlined in Section 2, this process produces twelve climatic projections, which are then classified for each country into DRY, AVG and WET scenarios. The forecast of cropland expansions is constrained by the choice of the specific SSP scenario selected for each simulation (cropland index of the SSP Database for the MENA region, Riahi et al., 2016) and estimated as projection of the current area under irrigation in each country (FAO, 2016a). Finally, given the expected development of more efficient irrigation systems in the area, we integrate into our agricultural water demand projections an analysis on the future trend of the country-specific irrigation efficiencies; such analysis, based on Alexandratos and Bruinsma (2012), forecasts a 9% average increase of the agriculture water use efficiency ratio for the Near East/North Africa region from 2005/2007 to 2050 (equivalent to ~0.2% per year). This increase is applied on an annual basis to each country-specific efficiency and modulated depending on the SSP scenarios selected for the calculation. In addition, to further modulate the possible developments in modern irrigation systems, we assign an overall +50% to the FAO's forecasted average increase for SSP1 (13.5% in 2050); for SSP2 we keep the same value (9% in 2050); a -50% for SSP3 and SSP5 (4.5% in 2050), and for SSP4 a +50% (13.5%) for the high-income countries (GNI per capita > 12,475 USD, according to World Bank classification) and 9% increase for the others.

The water demand for the industrial water sector refers to the water used in the production processes, which is either self-supplied or provided by a public supplier. In our case, it includes water for thermoelectric and nuclear power plants cooling systems and it serves industries not connected to the public distribution network. With municipal water demand, instead, we consider the water supplied through the public distribution network serving households, residential areas, and the part of the industries and urban farms that are connected to the municipal network (FAO, 2016a). The major drivers for the increase of domestic and industrial water demand are GDP and population growth, which cause rapid urbanization and competition among users and economic sectors to meet the needs of a growing world (Oki and Kanae, 2006). We calculate the industrial and municipal water demands of each country as the product between their net water intensities, IWI [m^3/MWh] and MWI [m^3/person], as defined by Alcamo et al. (2003), and the electricity production and population size, respectively. We first estimate the parameters of IWI and MWI, $ISWI_{min}$, $MSWI_{min}$ and $MSWI_{max}$, combining the available AQUASTAT data on the historical industrial and municipal water demands (FAO, 2016a), the countries' electricity production (extracted from the World Energy Outlook and World Bank databases, OECD/IEA, 2015) and population size in the same year of the FAO survey. Similarly, historical data on population and GDP for all the selected countries are retrieved from the World Bank database (World Bank, 2016a, b), while γ_i and γ_d, the remaining constant dimensionless parameters of IWI and MWI, are estimated by iteration. To forecast the future variation trends of the two net water intensities we use GDP and population projections from the SSP database for the MENA region. Finally, similarly to the approach used for agriculture water demand, we match the technological change in industrial and domestic water efficiency to the specific SSP scenario selected in the simulation, using the same ranges of variation (+50% in SSP1 and SSP4 high-income countries; no increase for SSP2 and SSP4 low and middle-income countries; -50% in SSP3 and SSP5).

Irrigation requirements for landscaping and recreational purposes, which are particularly substantial in the GGC countries (i.e. Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates), are accounted either in the municipal demand, if the source is public, or are met by the use of wastewater reuse (FAO, 2016a).

Fig. 5 shows the resulting projected aggregate water demand per economic sector from 2016 to 2050 for North Africa (5.a) and the Arabian Peninsula (5.b) in the case of the SSP2 and AVG climate change scenarios. The overall water requirements under these hypotheses will grow from 104 to 130 BCM (± 3.69) for North Africa (+25%) and from 34.2 to 50 BCM (± 1.07) in the Arabian Peninsula (+46%) by 2050. For both regions, the agricultural sector has the highest water needs, on average equal to 70–80% of the overall demand, growing at an almost constant pace of ~8% every decade. The industrial demand will instead grow at a much higher rate per decade: ~14% for North Africa and ~50% for the Arabian Peninsula, going from 5% to 17% of the total demand in 2050 for this latter region. The domestic water demand for both regions will remain almost constant, averaging at ~15-18% of the overall demand, despite the projected increase in population size for some of the North African countries.

Fig. 5c shows the forecasted aggregate water demand for each specific SSP scenario. SSP1 shows water requirements 5.2% lower than SSP2 in 2050, while SSP4, SSP5 and SSP3 present higher water demands of 8%, 32% and 43%, respectively, when compared to SSP2. Finally, according to scenario SSP2, future climatic variability for the North African region will cause an annual fluctuation of water demand for irrigation by ± 0.76% (about ± 0.89 BCM/yr.), while for the Arabian Peninsula, it will have a similar fluctuation effect with a projected range of ± 2.4% (about ± 1 BCM/yr.) on average (see Fig. 5d).

4. Modeling water supply

From a hydrological perspective, conventional water resources can be classified into two main categories: surface runoffs collected in rivers, streams, lakes and catchments (perennial, seasonal or intermittent) and groundwater contained in renewable or fossil aquifers. These resources are all dependent on the natural processes of the water cycle and are strongly influenced by the variability of regional climatic factors.

Harsh arid conditions, coupled with low precipitations and high levels of evaporation and evapotranspiration, make North Africa and the Arabian Peninsula region one of the driest and most water-scarce areas in the world. To compensate for the shortage of natural resources and the growing demand due to the increase of population, a few

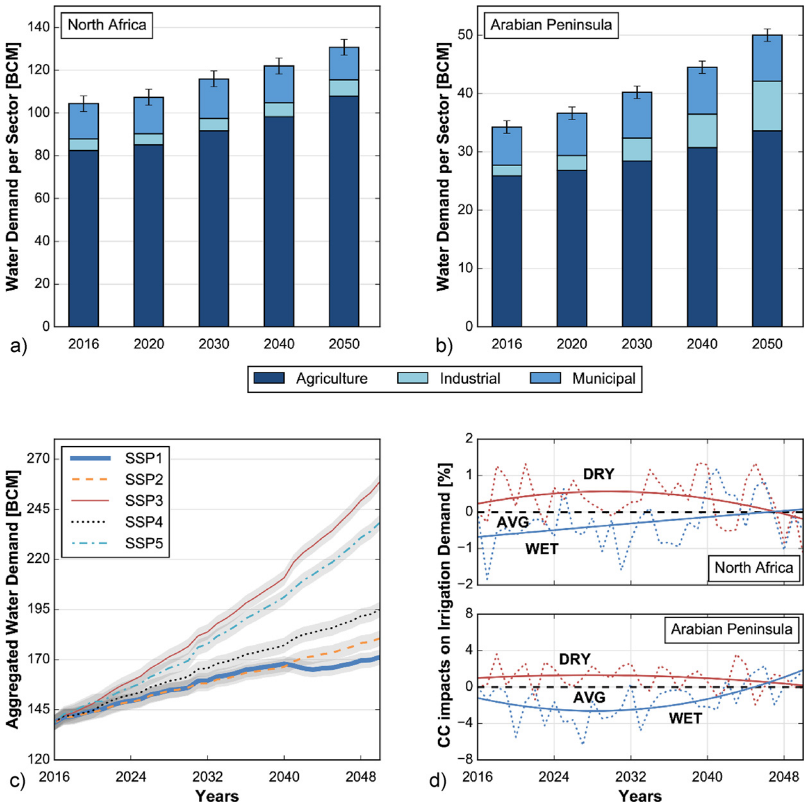

Fig. 5. Water demand projections per economic sector for North Africa (5.a) and the Arabian Peninsula (5.b) for the SSP2 and AVG scenario. (5.c) Aggregated water demand up to 2050 for the different SSP scenarios with AVG climate change. (5.d) Climate Change effects of the DRY and WET scenarios compared to AVG on the irrigation demand for the SSP2 scenario. The shaded grey areas highlight the error ranges in our model.

decades ago most of the MENA countries started to invest in non-conventional water resources, which offer a complementary supply of freshwater that can be used to partially alleviate their water scarcity.

In this section, we provide a brief description of the key characteristics of the main water supplies of North Africa and the Arabian Peninsula that we consider in our water budget model. We describe conventional sources differentiating between renewable and non-renewable. For non-conventional sources, we present the current status and the future projections on desalination capacity and wastewater reuse for each country.

4.1. Conventional water resources

Conventional water resources for Northern Africa and the Arabian Peninsula can be differentiated in renewable and non-renewable. The first ones are the total amount of a country's net water supply (internal and external), both surface water and renewable groundwater, mostly shallow groundwater, generated through the water cycle. On the contrary, non-renewable water resources mainly comprise fossil groundwater bodies characterized by a negligible rate of recharge, several orders of magnitudes lower and slower when compared to renewable groundwater systems (McDonnell, 2017). For this reason, we account for climate change effects only on renewable water resources supply, whether surface or groundwater. Fossil aquifers for the MENA region represent the dominant type of groundwater resources, while renewable aquifers constitute only a small fraction of the regional water budget.

4.1.1. Renewable resources

The MENA countries considered in our model present different availability of renewable water supplies. For instance, Algeria's and Tunisia's streams originate mainly from precipitation, snowmelt and runoff from the mountains; Egypt possesses surface and shallow subsurface waters related to the Nile Basin, while Libya, the GCC countries and Yemen do not have any relevant renewable source of surface water, having to rely only on groundwater – both renewable and non-renewable –, and on desalination (FAO, 2016a).

We compile the data on the availability of renewable freshwater resources for each country from the FAO AQUASTAT database (FAO, 2016a) and we compare them with other publications and governmental reports. According to the FAO database, renewable freshwater availability is defined as the average annual flow of rivers and recharge of aquifers generated from precipitation. In hyper-arid environments, the annual changes in the renewable water supplies are influenced by the regional climatic variability. Hence, we modulate the changes in supply according to the percentage change of the difference between annual precipitation and evapotranspiration. As in the case of the agricultural water demand, the climate change projections are adjusted with the DRY, AVG and WET scenarios derived from the calculation outlined in Section 2. A summary of the present total renewable water storages for each considered country is shown in Table 1.

Egypt, among the countries considered in this study, is the only one where renewable supply mostly originates outside of its territories. It is the last downstream riparian of the Nile river basin, which is shared with 10 other countries and composed by different sub-basins. The forecast of the Nile flow entering the Egyptian border is constrained by the interannual recharge variability and long-term climatic changes of the southern tropical region and the anthropogenic pressure caused by the upstream riparians.

The climate within this basin is extremely variable passing through very different climatic gradients, from humid equatorial in the south to semi-arid, arid and hyper-arid in the center/northern region. Precipitations have a significant interannual and decadal variability, with annual rainfall mostly concentrated in the upstream countries, such as the Rift Valley and the Ethiopian Highlands, while Egypt and Sudan exhibit very low amounts (Camberlin, 2009). The area of the basin that mostly contributes with significant volumes to the Nile flow is the Ethiopian Plateau, but it is however strongly affected by the seasonal rain patterns. The White Nile in the equatorial subsystem supplies a lower volume of water to the Nile, but it is characterized by a

Table 1
Total annual availability of renewable water in billions of cubic meters (BCM/year) for each considered country. Ref: [1] FAO, 2016a, [2] Hamiche et al., 2015, [3] Ansari, 2013 [4] Abdulrazzak, 1994, [5] Ismail, 2015, [6] Salem, 1992 [7] MRMWR, 2008, [8] Baalousha, 2016, [9], Abdulrazzak, 1995, [10] Shetty, 2004, [11] Ward, 2014.

Country	Renewable Surface Water	Renewable Groundwater	Overlap	Total Renewable Water Resources
Algeria	10.15 [1]	1.517 [1]	0 [1]	11.667 [1,2]
Bahrain	0.004 [1]	0.112 [1,3]	0 [1]	0.116 [1]
Egypt	56 [1]	2.3 [1]	0 [1]	58.3 [1]
Kuwait	0.001 [1,4]	0.02 [1,5]	0 [1]	0.02 [1]
Libya	0.2 [1,6]	0.6 [1,6]	0.1 [1]	0.7 [1,6]
Oman	1.05 [1,7]	1.3 [1,7]	0.95 [1]	1.4 [1]
Qatar	0 [1]	0.058 [1,8]	0 [1]	0.058 [1]
Saudi Arabia	2.2 [1,9]	2.2 [1]	2 [1]	2.4 [1]
Tunisia	3.42 [1]	1.595 [1]	0.4 [1]	4.615 [1,10]
U.A.E.	0.15 [1,10]	0.12 [1]	0.12 [1]	0.15 [1]
Yemen	2 [1]	1.5 [1,19]	1.4 [1]	2.1 [1, 11]

Table 2
Summary of the entry data for the fossil aquifer systems in North Africa and the Arabia Peninsula: exploitable storage available in billions of cubic meters [BCM], present annual recharge in BCM/year, present annual extraction in BCM/year (for the considered nations), and list of the riparian countries for each transboundary aquifer.

Aquifer Systems	Exploitable Volume	Recharge	Extraction	Riparian Countries
NWSAS	1,280 [1]	1 [2,3]	2.851 [4,a]	Algeria, Libya, Tunisia
Murzuq Aquifer	70 [1]	0 [5]	1.75 [1,4]	Libya, Niger
NSAS	10,217* [1]	0.005 [6]	2.531 [4,a]	Chad, Egypt, Libya, Sudan
Dibdibba - Kuwait Group	11 [7,8]	0.059 [7]	0.092 [7]	Iraq, K.S.A., Kuwait
Neogene Eastern Saudi Arabia	5 [9]	0.28 [a]	0.55 [a]	K.S.A.
Sand Dune - Liwa Aquifer	101 [10]	0.072 [11]	2.189 [12]	U.A.E.
Western Gravel Aquifer	20.6 [a]	0.03 [7]	0.446 [7]	Oman, U.A.E.
Ash Sharqiya Aquifer	24 [13]	0.07 [14]	0.08 [14]	Oman
UER / Dammam (South)	112.89 [7]	0.012 [7]	0.053 [7]	K.S.A., Oman, U.A.E
UER / Dammam (Center)	57.51 [7]	0.922 [7]	1.242 [7]	Bahrain, K.S.A., Qatar
UER / Dammam (North)	42.6 [7]	0.173 [7]	0.12 [a]	Iraq, K.S.A., Kuwait
Sakaka Aquifer	100 [7]	0.242 [7]	0.3 [7]	Iraq, K.S.A.
Wasia-Biyadh-Aruma Aquifer System	500 [11]	0.045 [7]	0.09 [a]	Bahrain, K.S.A., Yemen
Tawil Aquifer	22 [7]	0.03 [7]	0.876 [a]	Jordan, K.S.A.
Minjur - Dhruma Aquifer	182 [8]	0.08 [8]	5.4 [8]	K.S.A.
Saq-Ram (Tabuk) Aquifer	665.37 [7]	0.35 [7]	6.565 [7]	Jordan, K.S.A.
Wajid Aquifer	39 [7]	0.104 [11]	2.358 [7]	K.S.A., Yemen

* Share of Egypt and Libya only. Ref.: [a] Values calculated in this study, [1] Foster and Loucks, 2006, [2] CEDARE, 2014, [3] Schmidt, 2008, [4] OSS, 2004, [5] Ibeda et al., 2013, [6] Maliva and Missimer, 2012, [7] UN-ESCWA and BGR, 2013, [8] Al-Rashed and Sherif, 2000, [9] MOP (Ministry of Planning), 1985, [10] Brook et al., 2006, [11] Wagner, 2011, [12] MEW, 2010, [13] Al-Khamisi, 2011, [14] MRMWR, 2008.

more stable rainfall availability. The Main Nile area, extended over the downstream countries, generates instead a negligible runoff and presents high evaporation resulting in an overall net loss. Studies on climate change effects on the Nile basin at regional scale observe that there is no unique and clear indication of the climate change effects on the Nile flow (Conway, 2005). Barnes (2017), presents a thorough review of the latest climate change modeling studies for the Nile Basin and points out that the majority of the models agrees on the existence of an overall warming trend, while they present high degrees of uncertainty regarding the direction of changes in precipitation and streamflow.

Furthermore, the current and projected population increase and consequent growth in water demand is spreading the tension in the hydro-politics of the region. The downstream riparians, namely Sudan and Egypt, signed an agreement in 1959 for the full utilization of the Nile waters. This treaty assigns 55.5 BCM/yr. to Egypt, 18.5 BCM/yr. to Sudan and 10 BCM/yr. is accounted as annual evaporation at Lake Nasser/Nubia. In 2011, the unilateral announcement by Ethiopia of the construction of the Great Ethiopian Renaissance Dam (GERD) on the Blue Nile at the Ethiopian-Sudanese border and the independence of South Sudan from Sudan changed the hydro-political balance. Both these phenomena could additionally challenge the water management in the region adding uncertainty on the forecasts of the water availability in the downstream states.

Given the above mentioned complexities, obtaining a reliable prediction of the effects of climate change and water management planning in the Nile Basin is challenging and would require a separate and more detailed analysis. Therefore, we assume in our model that the maximum withdrawal from the Nile for Egypt is fixed at 55.5 BCM/yr. and we discuss the potential effects induced by climatic changes and population increase within the basin on the Egyptian water deficit in Section 5.1.

4.1.2. Non-renewable water resources

Most of the groundwater in the MENA area is contained in fossil aquifer systems that are the remnant of wetter or more humid geological eras (Bourdon, 1977 and 1982). All the countries examined in the model present one or more fossil aquifer systems within their borders. The Northern African Sahara area includes: the North Western Sahara Aquifer System (NWSAS), the Murzuq Aquifer and the Nubian Sandstone Aquifer System (NSAS). The Arabian Peninsula has nearly 30 different shallow and deep water-bearing and transmitting formations (Alsharhan et al., 2001). In our model, we distinguish and characterize the following: Dibdibba-Kuwait Group, Neogene Eastern Saudi Arabia, Sand Dune-Liwa Aquifer; Western Gravel Aquifer, Ash Sharqiya Aquifer, Umm Er Radhuma (North, Center and South), Sakaka Aquifer, Wasia-Biyadh-Aruma Aquifer System, Tawil Aquifer, Minjur-Dhruma Aquifer, Saq-Ram Aquifer, Wajid Aquifer. A summary of the main hydrological characteristics for all the non-renewable aquifer systems in both Northern Africa and the Arabian Peninsula is presented in Table 2.

Since desalination is the primary source of freshwater for most of the GCC countries, in our simulation we model the projections of increase in desalinated water capacity planned for the immediate future for each country. For each state, we collect the number of desalination plants that are currently active, their capacity and the year they started operating (data are retrieved from local public utilities or water ministries annual statistic reports). Assuming an average plant lifespan of 25 years, we estimate a first order approximation of future desalination capacity, which also accounts for the desalination plants that are under construction or that have been already commissioned. Therefore, we produce a realistic estimate of future desalination capacity trends for each country, up to 2050 (see Fig. 6a). In our simulations, we hypothesize that once each country reaches its maximum desalination production capacity (highlighted in red in Fig. 6a), it will keep this value constant for the remaining years. This is a reasonable assumption that serves as lower bound for our simulations, since it is plausible to expect that a country relying significantly on desalination will keep at least the same level of production of desalinated water in case of an increasing water demand. We assume that the country will replace each of its decommissioned desalination plants with a new one that has at least the same production capacity. Treated wastewater is instead mostly used for irrigation, in particular in North Africa. The high-income countries in the GCC use treated wastewater for agricultural and

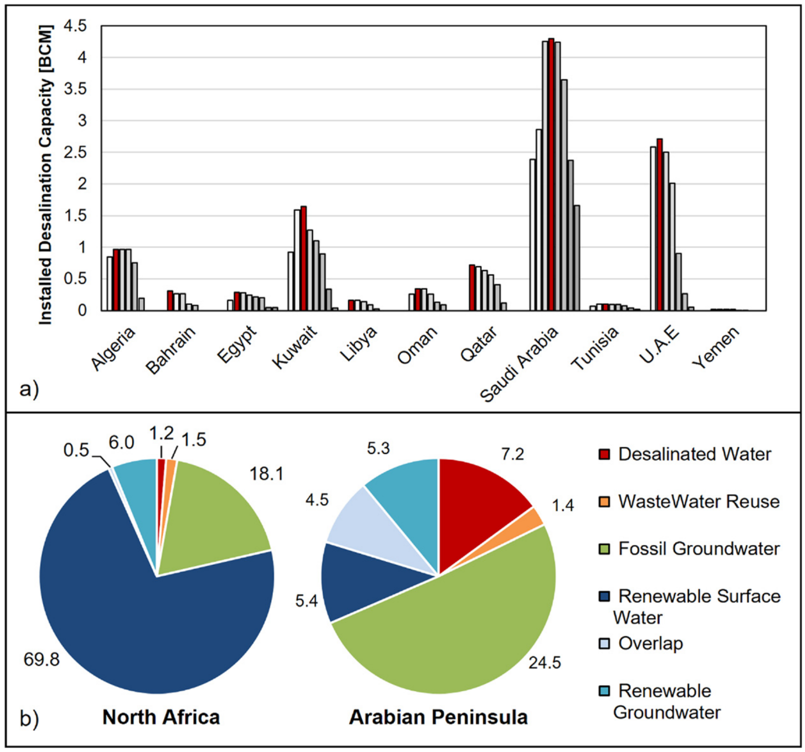

Fig. 6. Projected desalination capacity in BCM/yr. from 2016 to 2050 (6.a, self-calculation) and summary of the present conventional and non-conventional water resources in BCM for North Africa and the Arabian Peninsula (6.b, self-calculation based on FAO, 2016a).

landscape irrigation. The efficiency of wastewater treatment in the MENA region is highly variable, due to the inability of accommodating the large volumes of wastewater resulting from increasing urban populations. Forecasting future wastewater reuse in the MENA region is challenging. Although wastewater reuse is expected to grow and develop in the next future, little if no data is publicly available for most of the countries under study. For this reason, from 2016 to 2050, we hypothesize a constant rate of investments in wastewater reuse for each country, calculated as percentage over each nation's water demand. This assumption will give us as a lower bound for the forecasted water gap of each nation without affecting the accuracy of the predictions. Fig. 6b summarizes the overall water supply for the North Africa and the Arabian Peninsula.

5. Simulations and results

In this section we present the results of the calculated water budget under the different climatic and socio-economic scenarios considered for this study. The analysis has two major objectives:

1 Quantifying the projected water deficit per country, when holding constant the annual maximum fossil groundwater withdrawal to the present values of extraction (i.e. BAU study case). The goal is to measure and separate the effects of the projected rising water demands against the available conventional and non-conventional water supplies. In particular, our scope is to evaluate both how long the available renewable resources can sustain the increasing water requirements in the region and if the current planned investments in non-conventional water resources can mitigate or withstand this growing need.
2 Understanding if groundwater can be used as a natural strategic source to fulfill the projected water demand of the region by assessing the consequential depletion of the aquifers' storages. We perform this analysis within our simulations, allowing for the countries to increase their annual fossil groundwater demand to meet their water requirements (i.e. IGW study case).

5.1. Projected water deficit

The first step consists in the simulation of the projected water deficit that the considered MENA countries may undergo from 2016 up to 2050 under all the different SSPs and climate change scenarios. In Fig. 7a and b we present the resulting forecasted water gaps of the BAU study case under the SSP2-AVG scenario, selected herein as illustrative case for the countries in North Africa and in the Arabian Peninsula, respectively. We first observe that in North Africa, Algeria and Tunisia are not likely to suffer from any significant water deficit within the simulated time frame. On the contrary, Libya and Egypt will suffer significant freshwater shortages. In particular, Egypt, which is already experiencing a substantial water gap of ~11.40 BCM/yr. (±4.60), will further deteriorate its situation, reaching a three times larger deficit by 2050. This water gap corresponds to ~15% in 2016 and ~45% in 2050 of their freshwater supply. Even though Libya will face a smaller deficit in absolute value in 2050 (3.52 BCM/yr. (±1.17)), this amount is critical if compared to the available Libyan water supply (~90%). For Egypt, these results can be altered by the possible natural and anthropogenic variabilities in streamflow of the Nile River, induced by changes in precipitations and development of infrastructures along the Basin (i.e. urban and agricultural expansion, and dams). Beyene et al. (2010) forecast an increase in annual average inflow of 11–14% during 2010–2039, but a decrease of 7–8% for the period 2040–2069, while Siam and Eltahir (2017) suggest that the long-term mean and the standard deviation of the entire river flow could increase by 15% and 50%, respectively, compared to the twentieth century. On the demand side, the Nile Basin countries' total population is estimated at ~500 million in 2016, of which ~270 million live within the Nile Basin boundaries. Based on the SSPs projections considered in our study, the population growth for the riparians, excluding Egypt, is between 60% (SSP5) and 114% (SSP3) by 2050. This substantial increase will potentially affect the future water demand for the agricultural, industrial

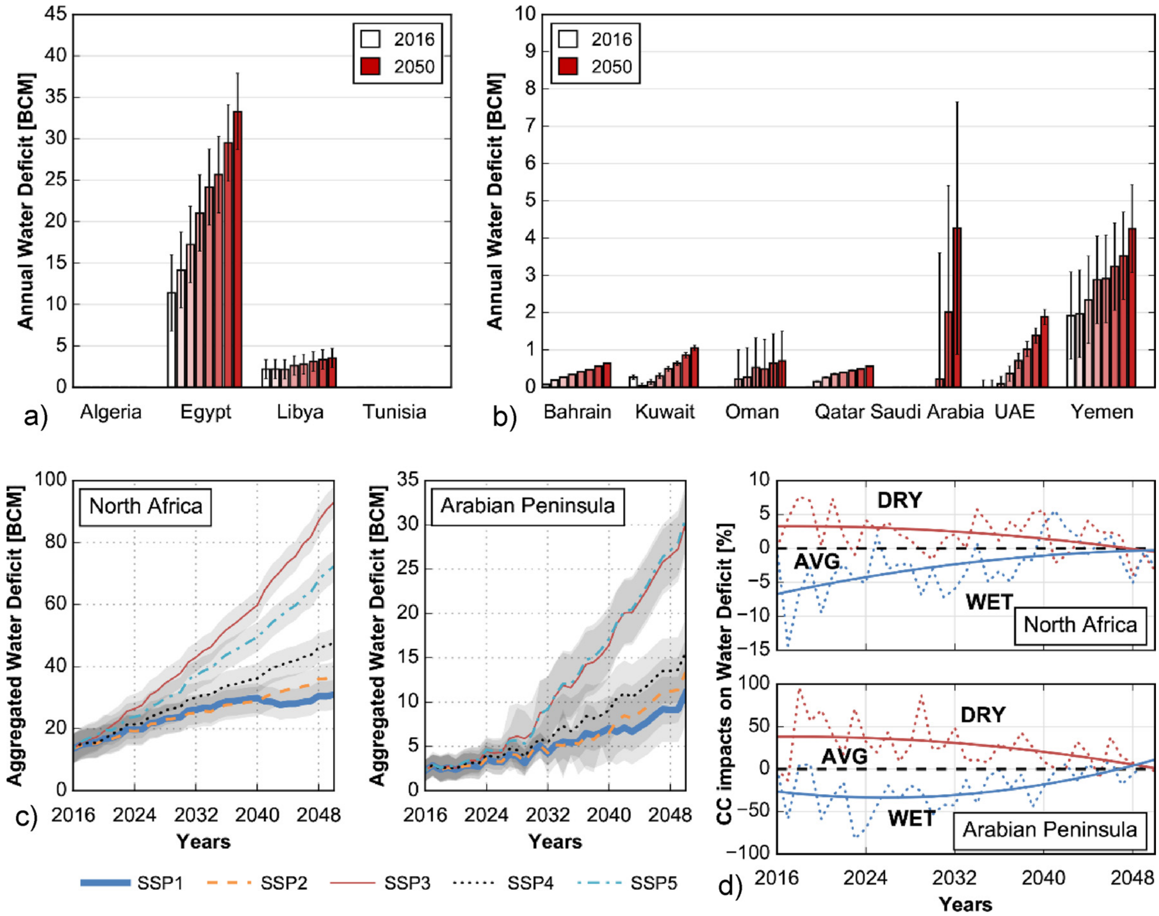

Fig. 7. Histograms of the calculated annual water deficit from 2016 to 2050 for the SSP2-AVG scenario for each country of North Africa (7.a) and of the Arabian Peninsula (7.b). Fig. 7.c presents the resulting aggregate water deficit for the two regions under the different SSP scenarios and the AVG climate. Fig. 7.d shows the additional effects produced by climate variability respect the AVG scenario of drier or wetter future climatic conditions on the SSP2 aggregate regional water deficit. The shaded grey areas highlight the error ranges in our model.

and municipal sectors. In particular, the current total withdrawn from the Nile to meet the irrigation water requirements is 82.2 BCM/yr., with Egypt, Sudan and Ethiopia accounting for 99% of the overall extraction (80%, 17% and 2%, respectively, Akol et al., 2016). Any further expansion of the irrigated land in Sudan and Ethiopia, aggravated by the ongoing process of land transfer to foreign investors, could result in increased withdrawals from the River. Moreover, the construction of hydropower dams in the upper Nile Basin could potentially decrease the availability of streamflow at the High Aswan Dam (Zhang et al., 2015), like the GERD, which could induce 6–14% average flow reduction during the first 5 years of filling operations (Digna et al., 2018). In summary, the short-term climate change effects on the Nile Basin could temporarily balance the increased demand for water resources for the riparian countries, but in the long-term this might not apply any longer, consequently harshening the water deficit that Egypt will experience after ~2030.

Among the countries of the Arabian Peninsula, Saudi Arabia and Yemen show the highest deficit level in 2050, ~4.26 BCM/yr., (±3.39 for Saudi Arabia and ±1.73 for Yemen), which accounts for the ~20% and ~190% of their freshwater availability, respectively. Saudi Arabia's water gap, in particular, starts growing by ~2 BCM per decade after 2040. Bahrain, Kuwait, Oman and Qatar share a similar forecasted deficit trend, which will reach ~0.74 BCM/yr. in 2050 on average (±0.007, ±0.07, ±0.79, and ±0.014, respectively). Although this volume seems low in absolute terms, if compared with the countries' supplies, it corresponds to ~108%, ~83%, ~40%, and ~60%, respectively. Finally, the U.A.E. will linearly increase its deficit of ~0.36 BCM/yr. every ten years, reaching 1.88 BCM/yr. (±0.2) in 2050 (~34% of its future supply).

If we consider the aggregate water deficit in 2050 calculated for the two regions in the SSP2-AVG scenario, which equals to 36.8 BCM/yr. (±4.74) and 13.4 BCM/yr. (±3.68), the variation induced by the selection of an alternative scenario in the same climatic conditions produces smaller water gaps for the SSP1 (-17% in average) and much greater for the other case studies. SSP4 induces a ~23% higher deficit, while SSP3 and SSP5 more than double the results of SSP2 (+139% and +114% in average, respectively; see Fig. 7c).

Ultimately, when accounting for the effect of climate change on the agricultural water demand and the renewable water supply, with respect to the average projection, we observe a water gap variation for the SSP2 scenario in North Africa between -2.7% and +2% in average (which translates in about -0.66 and +0.53 BCM/yr.). For the Arabian Peninsula, the overall effect will range between -19% and 20% on average, which equals to -0.91 and +1.36 BCM/yr. (see Fig. 7d). Among all the considered countries, Egypt and Yemen appear as the two most vulnerable countries to future climatic variability due to their strong dependency on renewable freshwater sources.

Fig. 8 instead, quantifies how much of the annual marginal increase in water deficit for every country is attributable to a decrease in their supply or increase in their water demand, averaged throughout the simulation and for each scenario (in % logarithmic scale). The colored bars display the deficit determinants for SSP2-AVG, while the error bars outline the range of variation when considering the effects of the other SSPs and climate change marker scenarios. We first observe that the

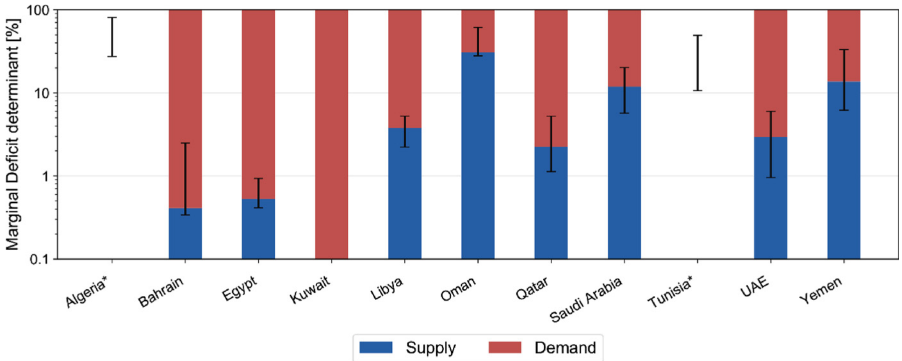

Fig. 8. Attribution of the annual marginal increase in water deficit per country (in % logarithmic scale). The colored bars show the deficit determinants for the SSP2-AVG and the error bars delineate the range of variation considering the effects of the remaining SSPs and climate change marker scenarios (SSP1-WET upper bound and SSP3-DRY lower bound for all countries; *countries with SSP5-WET upper bound and SSP3-DRY lower bound).

main determinant for the marginal increase of the deficit is the demand variation, while changes in supply have a much lower significance on the overall result, corresponding to less than 5% for 2/3 of the countries in deficit. Oman, Saudi Arabia and Yemen, display a supply deficit dependence at ~31%, ~12% and ~14%, respectively, reflected by the erratic presence in their territories of limited amounts of renewable water sources, which are instead completely absent in Kuwait. If we consider the other SSPs and climatic marker scenarios, we find that for most of the considered countries, the upper bound of variation of the marginal deficit dependency from the supply is achieved under the SSP1-WET scenario, while the SSP3-DRY defines its lower limit. The SSP1 is characterized by a low population growth, which substantially decreases after 2050, and a high but sustainable and efficient economic development, which both contribute to decrease the overall water demand. The WET marker scenario contributes instead to increase the water supply availability, thus decreasing the dependency of the deficit on this variable. At the same time, however, a wetter climate lowers the water requirements for irrigation, decreasing the overall demand. The combination of these two effects results on an overall higher dependency of the marginal deficit on the supply side. Conversely, the SSP3-DRY scenario, which represents the lower bound for most of the considered countries, portrays a world with slow economic development and a very high population growth that create high water demand and intense irrigation requirements. The impact of these phenomena, when combined with a scarcer supply, results in a higher dependency of the marginal deficit to the demand. Lastly, neither Algeria nor Tunisia experience any deficit under the SSP2-AVG along the considered timespan, but they display a measurable deficit only for the SSP3 and SSP5, which represent the lower (SSP3-DRY) and upper (SSP5-WET) bounds for these two countries, respectively.

5.2. Storage depletion

After evaluating the projected water deficit for each considered country, we test if the fossil groundwater systems in North Africa and the Arabian Peninsula can be used as strategic reserves to mitigate the increasing water demand of the region. Our goal is to weigh the effects of a higher groundwater withdrawal on the aquifer storage levels compared to the present conditions of extraction, accounting for all the socio-economic and climatic hypotheses at the base of our study. We present the results of this analysis for all the considered aquifer systems of the MENA region in Figs. 9–12. Every figure shows in the left column, for each aquifer, the % volume depletion relative to the current exploitable storage (*Relative* ΔV) under the AVG climate change scenario and for the different socio-economic hypotheses analyzed in this study. In particular, the overall groundwater depletion estimates for the BAU case study (current extraction rates are kept constant up to 2050) are compared to the five SSP scenarios (IGW). On the right side of the figures we outline the changes in percentage of volume variation indirectly produced by the different climatic projections (DRY and WET) relatively to the average climatic conditions (AVG). Although we clearly observe an alarming depletion trend for all the aquifer systems, some of these fossil resources are in danger of full exaustion even at the present conditions of extraction.

North Africa's extensive groundwater reserves, such as the NWSAS and the NSAS, are currently exploited by their riparian countries at a rate of 2.85 BCM/yr. and 2.53 BCM/yr., respectively, which will cause a loss of 5% and 0.87% of their initial volume by 2050 (Fig. 9, BAU). The supplementary withdrawal from the NWSAS would result in a overall volume depletion between ~9% (± 0.22%) for SSP1/SSP2, and ~11% (±3.58%) for SSP3. The NSAS' forecasted volume drop will reach levels more than ten times higher compared to the BAU scenario, ranging between ~8% (±0.26%) for SSP1/SSP2 and ~15% (±0.27%) in SSP3 (Fig. 9). In contrast, the Murzuq aquifer is already heavily overexploited by Libya today; this might lead to its complete depletion by ~2037 (Fig. 9, all scenarios). The effects produced by climatic variability will be limited to ± 0.34%, ±0.16% and ±3.99%, for NWSAS, NSAS and Murzuq volume change, respectively (Fig. 9). This variation will impact mostly the NSAS, with a resulting average annual variability in actual volumes of ±0.47 BCM/yr. From these results we estimate that, while the Murzuq aquifer is already in extreme danger, the NSAS and NWSAS can sustain these increased extraction rates at maximum for 300 (±80) and 250 (±50) years after 2050, respectively.

In the Arabian Peninsula, almost one third of all the available groundwater systems are heavily overexploited and at risk of major depletion under the present conditions of withdrawal (BAU scenario). In particular, the Neogene aquifer of Eastern Saudi Arabia, the Tawil, the Wajid and the Minjur-Drhuma aquifers are expected to reach their complete exaustion between 2035 and 2045 (Figs. 9, 10 and 12). The Liwa and the Western Gravel aquifers will see a drop of almost 70% of their present exploitable reserves (Fig. 10), while the Dibdibba-Kuwait Group, the central part of the Umm Er Radhuma and the Saq-Ram aquifers are expected to lose between ~34% and ~46% of their current volume (Figs. 9, 11 and 12). The remaining groundwater bodies will instead dysplay a decrease between ~1.5% and ~13% of their initial storage (Ash Sharqiya, UER-Dammam North and South, Sakaka and Wasia-Biyadh-Aruma; Figs. 10–12). The increased groundwater extraction needed to sustain higher demand of water will further deteriorate the already unsustainable situation of the region. The most impacted aquifer systems are the Dibdibba-Kuwait Group, which would reach full exaustion by 2050 for all the SSP scenarios (Fig. 9), the Ash Sharqiya aquifer, with a relative volume drop between ~32% (±11.53%) and ~64% (±11.92%) (SSP1 and SSP3, Fig. 10), and the UER-Dammam North that could lose from ~23% (±1.39%) up to ~80% (±1.77%) of its starting exploitable volume for the SSP1 and SSP5 scenario, respectively (Fig. 11). Similarly, the Liwa and the Western Gravel aquifers, which also reached a severe depletion in the BAU case study, could reach almost total depletion with higher extraction rates in all the SSP scenarios (Fig. 10). A lower drop in storage is observed for the UER-Dammam South and the Wasia-Biyadh-Aruma aquifers, which could lose an additional ~26% on average compared to their forcasted BAU depletion under the different SSP scenarios (Figs. 11 and 12).

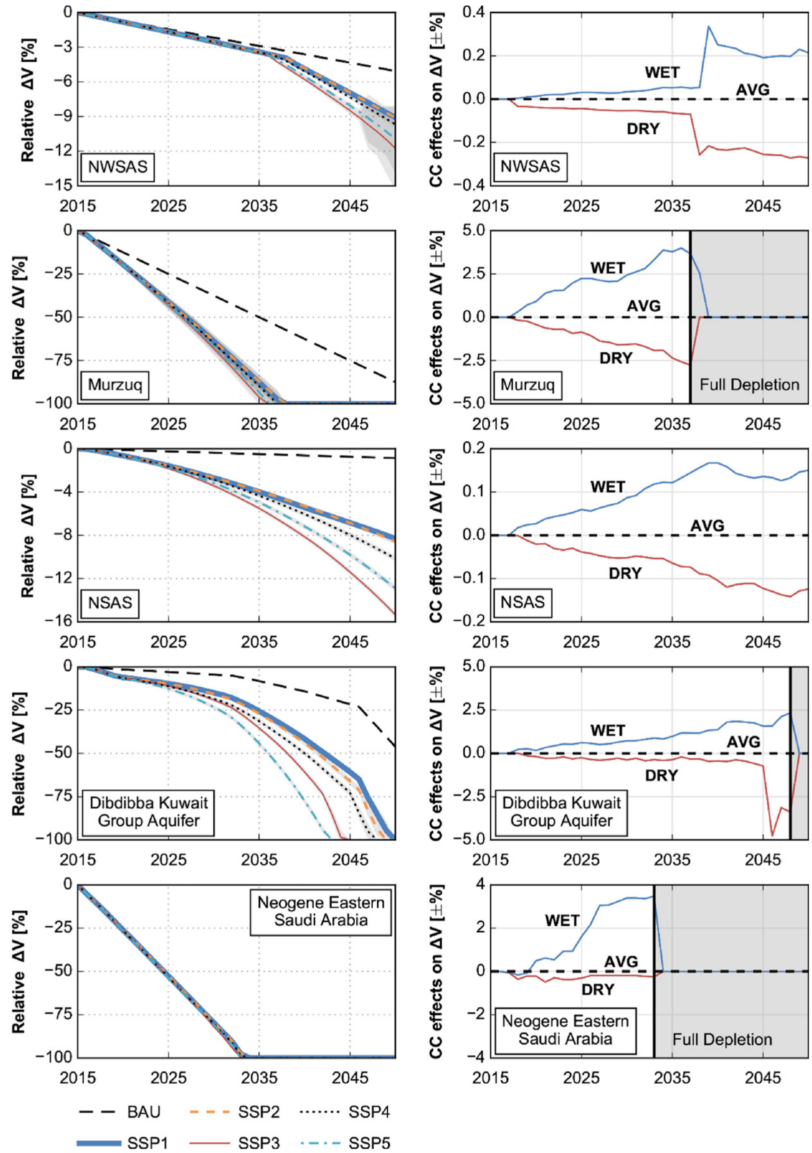

Fig. 9. Left column: calculated groundwater storage depletion normalized respect to the current exploitable volumes under the average (AVG) climate scenario both for BAU and IGW. Right column: additional percentage volume (%) variation due to wetter (WET) or drier (DRY) climatic projections relative to AVG. The shaded grey areas highlight the error ranges.

Finally, the Sakaka and the Saq-Ram aquifers will reach similar results to the BAU case study also under the different SSP scenarios (Fig. 12). The impact of climatic variability on the Arabian Peninsula strongly differ from country to country and among different aquifers. The smallest variation in both percentage and absolute value of storage for the WET/DRY scenarios are observed for the Tawil and the Sakaka aquifers, with an average ± 0.8% (0.5 BCM) on the resulting SSPs-AVG depletion simulations. On the contrary, the Ash Sharqiya and the Wasia-Biyadh-Aruma aquifers will face the largest uncertainty in terms of annual storage with -25/+12% (-6/+3 BCM) and ± 4.5% (± 22.5 BCM), respectively relative to the average scenario results. For the remaining groundwater systems, the effects of climate variability are limited to a relative average storage variation of ± 2% with respect to the average climate scenarios. The fossil aquifer resources of the Arabian Peninsula, which will not be fully depleted by 2050, sum up to ~1445 BCM in aggreagate and are currently exploited at a rate of ~7.96 BCM/yr. Accounting for the present extraction (BAU), a first order approximation of the average lifespan for these groundwater resources would be ~180 years. Instead, considering the higher projected extraction rates (IGW), this timeframe would shorten to 75 (±15) years.

6. Implications of water stress on socio-economic stability in the MENA region

The results of our water budget model quantify the severe water deficits and decrease in the exploitable fossil groundwater storage that the considered countries of the MENA region are likely to experience in the upcoming decades. The declines of groundwater levels are alarming also because exploitable aquifers serve as strategic reserves to mitigate periods of water shortages, driven by climatic variability and anthropogenic pressure (Tsur and Graham-Tomasi, 1991; Vouillamoz et al., 2015; Grönwall and Oduro-Kwarteng, 2018). Exploitable aquifers with relatively shallow fresh water differ from deeper ones with more saline and radioactive water that are more technically challenging and costlier to utilize as a water resource. Furthermore, as we approach the total volume depletion, water quality is more likely to rapidly degrade, further shortening the time scale of water availability to sustain the economic activities. As shown in our simulations, the present unsustainable use of these fossil resources, may lead to a rapid decrease in the water quality within the next two centuries.

As highlighted in our model, the agricultural sector is by far the

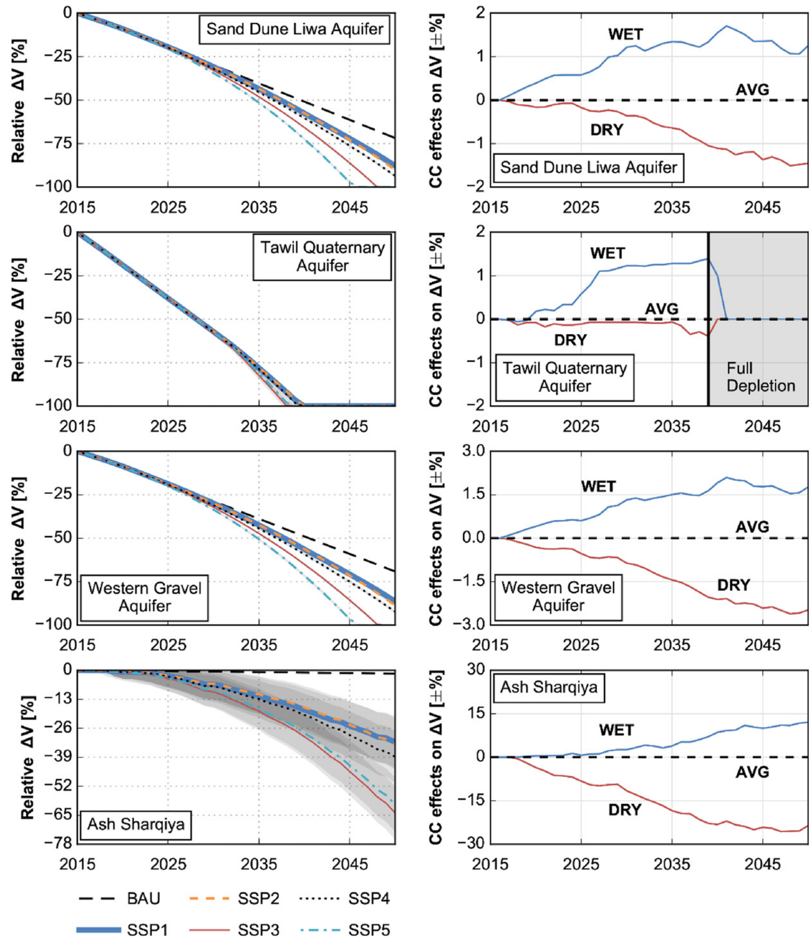

Fig. 10. Left column: calculated groundwater storage depletion normalized respect to the current exploitable volumes under the average (AVG) climate scenario both for BAU and IGW. Right column: additional percentage volume (%) variation due to wetter (WET) or drier (DRY) climatic projections relative to AVG. The shaded grey areas highlight the error ranges.

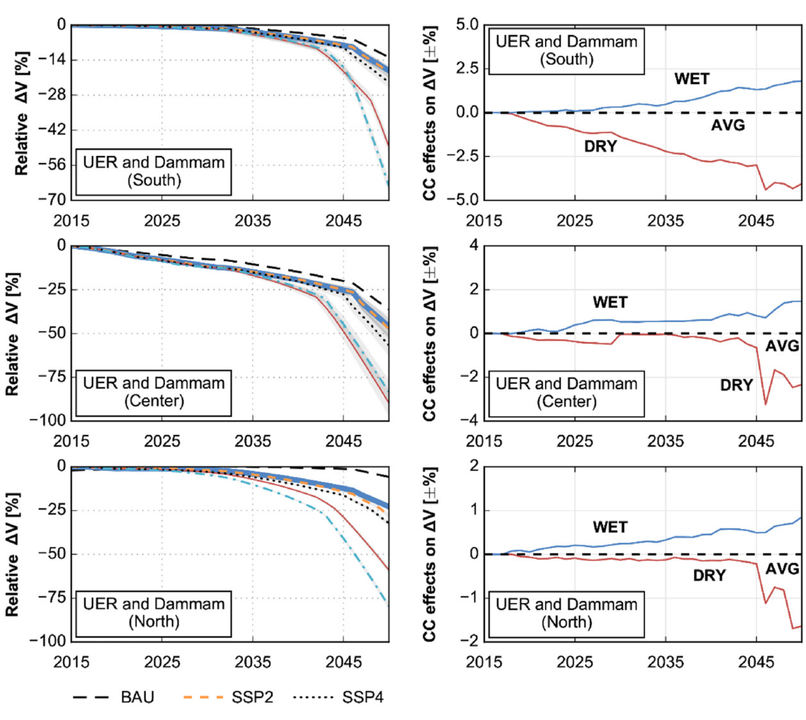

Fig. 11. Left column: calculated groundwater storage depletion normalized respect to the current exploitable volumes under the average (AVG) climate scenario both for BAU and IGW. Right column: additional percentage volume (%) variation due to wetter (WET) or drier (DRY) climatic projections relative to AVG. The shaded grey areas highlight the error ranges.

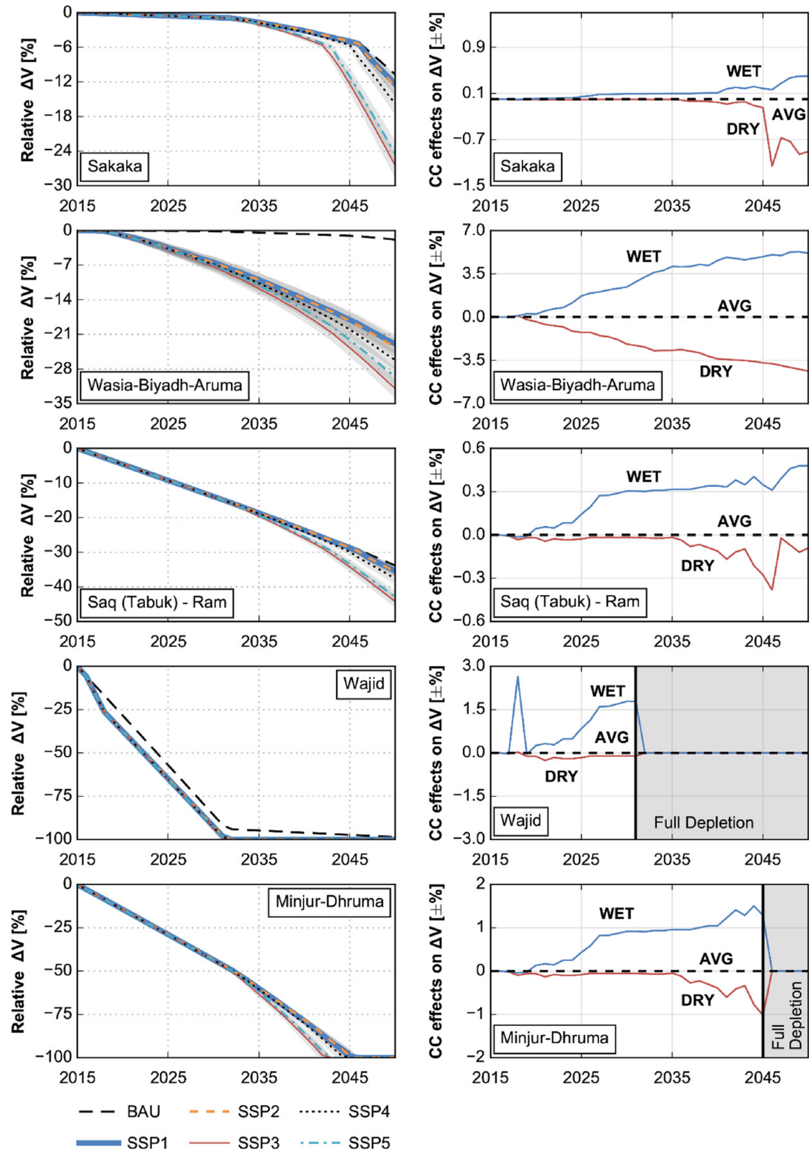

Fig. 12. Left column: calculated groundwater storage depletion normalized respect to the current exploitable volumes under the average (AVG) climate scenario both for BAU and IGW. Right column: additional percentage volume (%) variation due to wetter (WET) or drier (DRY) climatic projections relative to AVG. The shaded grey areas highlight the error ranges.

largest user of water, mostly employing groundwater (Hötzl, 2008; Faysse et al., 2011; Shah, 2014); Egypt is the only country that relies almost entirely on surface water from the Nile Basin (Karajeh et al., 2011). Therefore, the current and forecasted increasing water demand, aggravated by steady demographic growth and a dietary transition development (ElObeid and Hassan, 2014; Seyfert et al., 2014), directly correlate to the ongoing depletion of water resources, which in turn can cause serious threats to food production in the area. Additionally, the high dependency of the North African and Arabian Peninsula countries on food imports contributes to further deteriorating the food security for these nations. These countries are indeed much more susceptible to fluctuations of global food prices and stocks availability (Breisinger et al., 2010; Khouri and Byringyro, 2014), as it has been observed in 1973, and more recently in 2007–2008 and in 2011 (Eckstein and Heien, 1978; Holt-Giménez and Peabody, 2008; Larson et al., 2013). The connection between water stress and food security is illustrated in Fig. 13, where countries' water deficit per capita in 2016 and 2050 and GDPP (red dotted line) are plotted. Two main groups are identifiable in Fig. 13: (1) *High* and (2) *Mid-Low Vulnerability in Food Security*. For the first group, comprising Yemen, Egypt and Libya, domestic agriculture is an important source of food supply and employment for a substantial share of the population. For instance, Egypt produces ~60% of its food supply (Sarant, 2017), while Libya and Yemen ~20% (WFP, 2011; FAO-GIEWS, 2017); the agricultural sector accounts for ~27% of the total employment for the three countries (World Bank, 2016c). Moreover, the above-mentioned countries exhibit high water deficits per capita and low GDPP. The second group, *Mid-Low Vulnerability in Food Security*, includes the GCC countries, which, unlike the first group discussed above, are heavily dependent on food imports. For instance, agriculture represents ~2% of value added to GDP of Saudi Arabia and Oman, while agricultural revenue in Kuwait, Bahrain, Qatar and the UAE is negligible (World Bank, 2016c). The countries in this second group also suffer from high water deficits, but in contrast to the previous group, they are characterized by some of the highest GDPPs in the world (World Bank, 2016d), which would allow them to plan strategies to mitigate food security threats. The GCC countries have already secured their food supplies from foreign markets and are also expanding their domestic food storage capacity (UNDP, 2013). Finally, other countries such as Algeria and Tunisia (not shown in Fig. 13), will not be affected by water deficits within the time-scale of our model, although

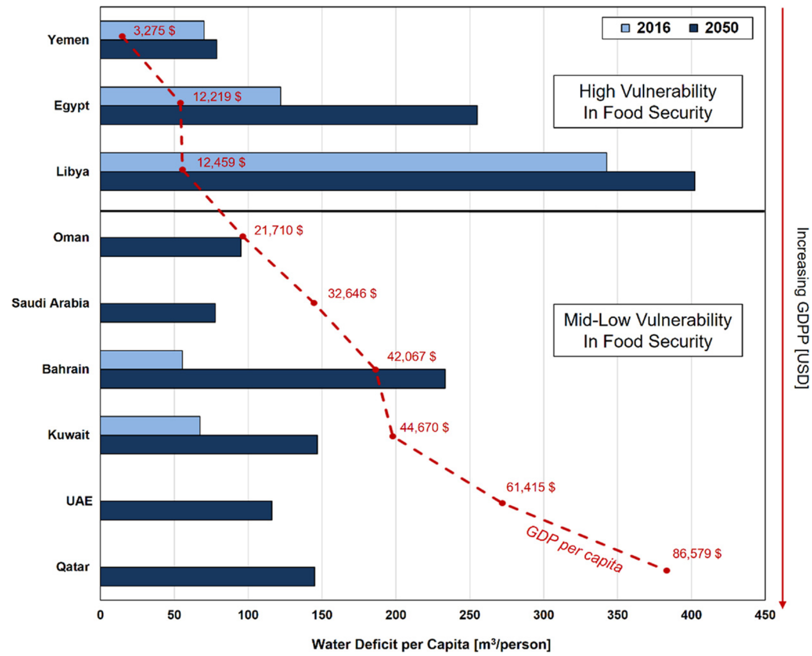

Fig. 13. Comparison for scenario SSP2-AVG of countries' water deficit per capita in 2016 (real) and 2050 (projected). Country listed from top to bottom according to their forecasted GDPP level for 2050.

they could exhibit scattered water deficits starting in 2045 and only under the SSP3 and SSP5 scenarios. The differences and discrepancies among the countries and within the two groups will definitely dictate the possible responses to food and water issues. Finally, our results conclude that the exploitable part of some of most used fossil aquifers, especially in the Arabian Peninsula, will completely exhaust even before this mid-century. Response time on new water management plans will therefore be a key parameter in elaborating effective mitigation and adaptation options.

7. Conclusions

The countries analyzed in our model already display diminishing water storage availability due the increase in water demand of the last decades, as observed by Rodell et al. (2018). Our study confirms that also future projections of water budget deficit and groundwater depletion will be mostly attributable to anthropogenic drivers rather than climatic one. In North Africa, Egypt and Libya will further aggravate their respective national water shortages by ~192% (+21.88 BCM/yr.) and ~62% (1.35 BCM/yr.) due to their increasing population size and agricultural development in the upcoming decades (2016–2050) under the SSP2-AVG scenario. Algeria and Tunisia may experience small deficits starting in 2045, but only under the SSP3- and SSP5-AVG climatic scenarios, ranging between 1.08 and 1.26 BCM/yr. (±0.85). In the Arabian Peninsula, our model forecasts substantial water deficits for all the GCC countries with different temporal scales and magnitude. For instance, Bahrain, Kuwait, Oman, Qatar, and the UAE are either already suffering water shortages or will start to face water deficits between 2020–2025, with values between 0.56 and 1.88 BCM/yr. (±0.165) by 2050, respectively. Saudi Arabia will reach a negative water balance of 0.21 BCM/yr. in 2040 and is projected to grow up to 4.05 BCM/yr. (± 3.39) in the successive decade. For Yemen, the results are similar to the North African countries: the scarcity of renewable water, coupled with a lack of investments in alternative water supply technologies, will linearly increase Yemen's present water deficit in the next decades by as much as ~121% (2.33 BCM/yr. (±1.73)). Conversely, in the GCC, the absence of surface water resources is balanced by the fast development of alternative sources of water (e.g. desalination and wastewater reuse), but their mitigation efforts may still not be able to fully meet increasing water demands, if consumption rates continue to rise and if the degradation of seawater quality persists, due to increased salinity and pollution.

When considering the pressure on fossil groundwater resources, we find that the Murzuq aquifer in North Africa and most of the small to mid-size fossil aquifers in the Arabian Peninsula could reach full depletion by 2050. The NWSAS and the NSAS in North Africa could sustain higher exploitation rates for ~200-350, while the exploitable part of the remaining water bodies in the Arabian Peninsula could be depleted within ~60-90 years. Our uncertainty analysis suggests that the mean error in these water deficit forecasts is smaller than ~12% and within ±3% for the storage depletion.

Finally, our projected water deficit and groundwater depletion (i.e. water stress) could induce a substantial rise in domestic food production costs that could in turn increase local food prices and/or the countries' dependency on foreign markets. The implication of these effects will induce additional socio-economic uncertainties to the highly vulnerable low-income countries, which are unable to mitigate markets' price fluctuations. In contrast, the GCC countries have the economic potential to address these food price increases, although they will have to consider that these impacts will unevenly affect households with different income levels.

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